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An automated and fast approach to detect single-trial visual evoked potentials with application to brain–computer interface

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HIGHLIGHTS

- A joint spatial–temporal–spectral filter combining common spatial pattern and wavelet filtering can significantly increase the signal-to-noise ratio of single-trial visual evoked potentials.
- The proposed approach can obtain robust and reliable visual evoked potentials in an automated and fast manner, thus satisfying the requirements of practical brain–computer interface systems.
- The proposed approach can be potentially used to achieve real-time and automated detection of single-trial evoked potentials or event-related potentials in various paradigms.

ABSTRACT

Objective: This study aims (1) to develop an automated and fast approach for detecting visual evoked potentials (VEPs) in single trials and (2) to apply the single-trial VEP detection approach in designing a real-time and high-performance brain–computer interface (BCI) system.
Methods: The single-trial VEP detection approach uses common spatial pattern (CSP) as a spatial filter and wavelet filtering (WF) a temporal–spectral filter to jointly enhance the signal-to-noise ratio (SNR) of single-trial VEPs. The performance of the joint spatial–temporal–spectral filtering approach was assessed in a four-command VEP-based BCI system.
Results: The offline classification accuracy of the BCI system was significantly improved from 67.6 ± 12.5% (raw data) to 97.3 ± 2.1% (data filtered by CSP and WF). The proposed approach was successfully implemented in an online BCI system, where subjects could make 20 decisions in one minute with classification accuracy of 90%.
Conclusions: The proposed single-trial detection approach is able to obtain robust and reliable VEP waveform in an automatic and fast way and it is applicable in VEP based online BCI systems.
Significance: This approach provides a real-time and automated solution for single-trial detection of evoked potentials or event-related potentials (EPs/ERPs) in various paradigms, which could benefit many applications such as BCI and intraoperative monitoring.

1. Introduction

Brain–computer interface (BCI) is an emerging technology which can establish a pathway between the human brain and computers through recording and decoding brain activity (Wolpaw et al., 2002). Since the control of BCI system is directly based on the recorded brain activity without the involvement of neuromuscular system, it allows people who suffer from motor dysfunction or impairment (e.g., amyotrophic lateral sclerosis, brainstem stroke, and spinal cord injury) to communicate with the external world or control prosthesis (Vaughan et al., 2003). In addition, BCI plays an important role in neurofeedback training (Strehl et al., 2006), and can be used by healthy people in various applications, such as computer game control (Hjelm and Browall, 2000; Lalor et al., 2005) and music generation (Miranda, 2010).

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Most existing BCI systems use electroencephalogram (EEG) to capture information on the subject's intention for controlling external devices (Niedermeyer and Da Silva, 2005). Visual evoked potentials (VEPs), which are phase-locked EEG responses evoked by visual stimulation, are one of the most extensively used EEG signals in BCI systems (Bin et al., 2009). According to the stimulus sequence modulation approach used, VEP-based BCI systems can be categorized into three types: (1) time modulated VEP (t-VEP) BCI, where stimulus sequences of different targets have independent and random flash onsets (Guo et al., 2008; Lee et al., 2006, 2008); (2) frequency modulated VEP (f-VEP) BCI, where stimuli are flashed at different frequencies (Allison et al., 2008; Jia et al., 2007; Middendorf et al., 2000; Müller-Putz et al., 2005); (3) code modulated VEP (c-VEP) BCI, where stimuli are encoded in pseudorandom binary sequences (Hanagata and Momose, 2002).

Recently, we have proposed a new encoding/decoding scheme for BCI based on chromatic transient VEP (CTVEP), which is evoked by low-frequency isoluminant chromatic stimuli for the purpose of minimizing the risk of eliciting epileptic seizures and reducing visual fatigue (Lai et al., 2011). In the CTVEP-BCI system, isoluminant chromatic stimuli are time-encoded into different binary codes ("1": presence of a visual stimulation; "0": absence of a visual stimulation), which are flickered simultaneously in different positions on the screen to serve as different input commands. Users can operate the BCI system by gazing at the target visual stimulation, and the user's intention can be decoded by calculating and comparing correlation coefficients between the code modulated CTVEP signals and CTVEP templates of different binary codes. Because the low-amplitude CTVEPs are usually buried in high-amplitude background of ongoing EEG and other non-cortical artifacts (Hu et al., 2010), the signal-to-noise ratio (SNR) of single-trial CTVEPs is very low, and reliable code-modulated CTVEPs were obtained by averaging EEG recordings of three identical epochs (Lai et al., 2011). This averaging approach could markedly enhance the SNR of CTVEPs, but greatly reduced the speed of the CTVEP-BCI system.

To achieve a high-speed and high-accuracy VEP-based BCI system, a fast and reliable approach to detect VEPs in single trials is highly desirable. Spatial filtering, which separates stimulus-elicited brain responses (e.g., VEPs) and ongoing EEG activity (or non-cortical artifacts) based on their distinct scalp distributions, has been popularly adopted to enhance the SNR of evoked potentials (EPs) and event-related potentials (ERPs) (Hu et al., 2011). One dominant spatial filter used is independent component analysis (ICA) (Makeig et al., 1996, 1997), which can identify and remove non-cortical artifacts, such as electrical activities related to eye blinks, eye movements, and muscle movements. In addition, temporal–spectral filtering, such as discrete wavelet filter (Quian Quiroga and Garcia, 2003) and continuous wavelet filter (Hu et al., 2010), can provide a time-varying filter based on time–frequency patterns of single-trial EPs/ERPs.

However, to the best of our knowledge, few single-trial EP/ERP detection methods have been successfully applied to real-time BCI systems for the following reasons. First, most available single-trial EP/ERP detection approaches are computationally demanding. Second, some techniques used for single-trial EP/ERP detection need intensive manual operation and cannot be executed automatically. Third, some spatial filtering techniques (such as ICA) only perform well on high-density EEG recordings (e.g., >16 channels), while a few-channel montage is more favored in practical BCI systems (Blankertz et al., 2011). To address these problems, we proposed an optimal filter by jointly utilizing distinct characteristics of VEPs in spatial, temporal, and spectral domains. This joint spatial–temporal–spectral filter was achieved by combining a common spatial pattern (CSP) based spatial filter and a wavelet filtering (WF) based temporal–spectral filter (Hu et al., 2010). The performance of the proposed spatial–temporal–spectral filter was evaluated by means of the SNR of single-trial CTVEPs, and the effectiveness of the proposed approach in the CTVEP-BCI system was assessed using classification accuracy. Furthermore, EEG data from fewer channels (i.e., 9, 7, and 5 channels) were used to evaluate the robustness of the single-trial VEP detection approach. Finally, the proposed approach was applied in a four-command VEP-based real-time BCI system, and its performance was evaluated in terms of information transfer rate.

2. Methods

2.1. Experimental design and EEG data collection

Eight healthy subjects (four males and four females) aged 21–25 years participated in the study. All subjects had normal or corrected-to-normal vision of $\geqslant$20/20 Snellen visual acuity, and were classified as normal color vision by the Ishihara test and the Farnsworth-Munsell 100-Hue test. No previous ocular or systemic disease was reported for these subjects. All subjects gave their written informed consent, and the local ethics committee approved the experimental procedures.

In each experiment, the subject was seated in a comfortable chair in a dim and unshielded laboratory with reasonable activities to simulate real-life situation. EEG signals were recorded using 13 Ag/AgCl channels positioned around the visual cortex based on the NeuroScan Quik-cap electrode placement system (Compumedics NeuroScan, El Paso, TX, USA) with bandpass filtering of 1–30 Hz and a sampling rate of 1 kHz. Channels *Fz* and *Cz* were respectively used as ground and reference, and impedances of all channels were kept below 10 kΩ.

2.1.1. Offline BCI experiment

In the offline experiment (Fig. 1), subjects were instructed to gaze at the stimuli binocularly, and the viewing distance was 100 cm. Isoluminant red-green circular sinusoidal gratings with spatial frequency of 2 cpd were presented on a Dell 17.3″ HD + Anti-Glare LED-backlit monitor (Dell, Round Rock, TX, USA). The monitor's refreshing rate was 60 Hz, and the resolution of the screen was 1600 × 900 pixels (equivalent to 22° × 12°). In the CIE XYZ coordinate system, red was defined as $x = 0.406$, $y = 0.287$; green was defined as $x = 0.223$, $y = 0.374$. Their mean was $x = 0.314$, $y = 0.330$ with a mean luminance of 20 cd/m^2. Note that (x, y) represented the chromaticity coordinate in CIE 1931 XYZ color space, and the background was kept unchanged at the mean chromaticity and luminance. The stimulus had a diameter of 2° with a small black dot acting as the fixation center. Our previous study showed that such a configuration of visual stimulation could maximize the amplitude of CTVEPs (Lai et al., 2011). Chromatic stimuli were presented in a pattern onset/offset configuration. Precisely, a visual stimulus presented for 50 ms and then absented for 200 ms denoted the "1" bit, while one silent cycle without any visual stimulus for 250 ms denoted the "0" bit. We encoded the visual stimulation into six 4-bit binary codes, each containing two "1"-bits and two "0"-bits (1–1–0–0, 1–0–1–0, 0–1–0–1, 1–0–0–1, 0–0–1–1, 0–1–1–0), for these codes achieve a good tradeoff between the number of control inputs and the quality of input signals (Lai et al., 2011). In this study, four codes (1–1–0–0, 1–0–1–0, 0–1–0–1, 0–1–1–0) were used in the four-command BCI system (Fig. 1).

The offline experiment consisted of two sessions: a training session and a test session. The training session was used to obtain CTVEP templates for each subject, and the test session was used to validate the performance of the proposed spatial–temporal–spectral filter. In the training session, 20 segments of visual stimuli,